

# **PORTABLE X-RAY DIFFRACTOMETER**

## **CROSS-REFERENCE TO RELATED APPLICATION**

5           This application is a continuation U.S. Utility Patent Application Ser. no. 10/102,992, filed March 21, 2002, which claimed priority to U.S. provisional application Ser. no. 60/355,200, filed February 8, 2002.

## **TECHNICAL FIELD**

10           The present invention is generally related to the examining of the internal structure of materials and, more particularly, is related to a system and method for the non-destructive internal examination of a material.

## **BACKGROUND OF THE INVENTION**

15           Metal fatigue can lead to catastrophic failure of a component or system. In power plants, oil refineries, chemical plants, or the like, metal tubes are subjected to pressures and temperatures that cause the tubes to become fatigued or to undergo creep. Metal components can also become fatigued from loading and unloading. For example, the landing struts of an airplane are subject to metal fatigue caused by the impact of landing the aircraft.

20           Frequently, metal components that are prone to fatigue are replaced according to a predetermined maintenance schedule, so as to avoid catastrophic failure of the metal components, which can cause the loss of life, injuries, and economic losses. However, the premature replacement of metal components can also lead to economic loss and other risks. Thus, it is desirable to examine metal components to determine their structural integrity so that they can be replaced before catastrophic failure, but not prematurely. Such an examination needs to be non-destructive.

A non-destructive method for examining the internal structure of a metal component is x-ray diffractometry. However, there have been problems associated with x-ray diffractometry outside of a controlled environment. For example, people and sensitive equipment can be harmed and damaged by being irradiated with penetrating radiation. In addition, radioactive materials, which are inherently dangerous and difficult to work with, are frequently used as sources in radiography.

Thus, it is desirable that an examination of a metal component be performed without a radioactive source. Furthermore, it is desirable that the examination occurs in situ. In situ examination of a component can typically be done more rapidly and inexpensively than non-in situ because there it requires less disassembly and reassembly of the system. It is also desirable that the apparatus used for examining the metal component be readily transportable and adapted to be used where there is no local electricity.

Thus, a heretofore-unaddressed need exists in the industry to address the aforementioned deficiencies and inadequacies.

### BRIEF DESCRIPTION OF THE DRAWINGS

Many aspects of the invention can be better understood with reference to the following drawings. The components in the drawings are not necessarily to scale, emphasis instead being placed upon clearly illustrating the principles of the present invention. Moreover,  
5 in the drawings, like reference numerals designate corresponding parts throughout the several views.

FIG. 1A is a perspective view of an exemplary crystal lattice.

FIG. 1B is a side view of planes of atoms in a crystal diffracting incident x-rays.

FIG. 1C a perspective view of a polycrystalline material diffracting x-rays.

10 FIG. 2A is a perspective view of a portable x-ray diffractometry apparatus for examining the internal structure of an object, in accordance with one preferred embodiment of the present invention.

FIG. 2B is block diagram of a central office that determines the remaining lifetime of a scanned object, in accordance with one preferred embodiment of the present  
15 invention.

FIG. 3 is a perspective view of components in the scanning head of FIG 2A.

FIG. 4 is a front view of a shuttered window in the scanning head of FIG 2A.

FIG. 5 is a schematic of one preferred embodiment of an x-ray source controller.

FIGs. 6A and 6B are example pictures of measured x-ray intensities.

20 FIG. 7 is an example plot of the x-ray intensity versus radial distance.

FIG. 8 is a flow chart of one example method for determining the radial distance from a central point for pixels in an x-ray detector.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

A brief description of x-ray diffractometry is provided hereinbelow. For further details, one can see "Introduction to Solid State Physics" Charles Kittell, John Wiley & Sons, which is hereby incorporated by reference in its entirety.

5 Referring to FIG. 1A, a crystal 1000 is made up of atoms 1002, which are periodically repeated. The exemplary crystal 1000 shown in FIG. 1A is a cubic crystal having a lattice constant of unity. In a cubic crystal each atom 1002 has six equidistant nearest neighbors. Thus, the atom located at the origin (0,0,0) has the following nearest neighbors:  $\pm(1,0,0)$ ,  $\pm(0,1,0)$ , and  $\pm(0,0,1)$ . In a crystal there are many intersecting planes  
10 of atoms, and the [1,1,0] and [1,1,1] planes are shown in FIG. 1A. The [1,1,0] plane is represented by the box having atoms located at its corners, and the [1,1,1] plane is represented by the shaded triangular region having atoms located at its vertices. The designation for a plane is determined by finding the intercept of the plane with each axis (when a plane does not intersect an axis, the intercept is considered to be infinite); and  
15 then taking the reciprocals of the intercepts and reducing them to the three smallest integers having the same ratio. For example, a plane that intersects the x-axis at  $\frac{1}{2}$  and does not intersect the y-axis and the z-axis has the planar designation of [2,0,0]. Whereas, a plane that intercepts the x-axis at 2, the y-axis at 3, and the z-axis at 4, would be designated the [6,4,3] plane.

20 Referring to FIG. 1B, the crystal 1000 includes parallel planes 1003 of atoms 1002 that are separated by a distance  $d$ . In FIG. 1B, incident x-rays 1004 are diffracted by the parallel planes 1003 of atoms 1002, which means that the angle of incidence  $\theta$  equals the angle of reflection. W.L. Bragg discovered that at certain angles there are peaks in the intensity of the reflected x-rays 1006. These angles are  
25 known as Bragg angles and can be determined from the Bragg equation:

$$2d \sin(\theta) = n\lambda,$$

where  $d$  is the planar separation,  $\theta$  is the angle of incidence (and reflection), and  $(n\lambda)$  is an integral number of wavelengths of the x-ray beam. The x-rays reflected from the second plane of atoms 1003(B) travel a different and longer path than the x-rays reflected from the first plane of atoms 1003(A). The difference in the path is shown by the dashed

line 1008. Bragg's law simply relates the path difference between x-rays that are reflected from different planes to the wavelength of the x-rays. When the path difference is an integral number of wavelengths, the reflected x-rays exhibit constructive interference and a peak in the intensity is observed. Typically, a plane of atoms reflects only a small percentage of the x-rays that are incident upon it, approximately 0.001%-0.1%. Thus, incident x-rays 1004 penetrate deep into the crystal with each plane of atoms reflecting only a fraction of the incident x-rays.

In a polycrystalline material such as a metal, the material is made up of small grains of randomly oriented crystalline regions. In such a material, the incident x-rays 1004 are reflected from many grains, and because of the random orientation of the grains the incident x-ray beam 1004 is reflected in a cone. The center of the cone has an axis that is co-linear with the propagation direction of the incident x-rays. In FIG. 1C, incident x-rays 1004 are reflected from a polycrystalline material 1010. The reflected x-rays 1006 are diffracted into a cone having a central axis 1005, which is co-linear with the propagation direction of the incident x-rays 1004. Here, the angle between the central axis 1005 and the reflected beam 1006 is  $2\theta$ , where  $\theta$  is the angle between the incident x-rays 1004 and the plane 1003 of atoms 1002 that reflect the incident x-rays 1004. In the preferred embodiment of the invention, a detector (not shown) is positioned to intersect with the cone and detect a portion of the diffracted x-rays along arc 1012. Because the grains in the polycrystalline 1010 are generally oriented in a random distribution, the intensity of the reflected x-ray beam 1006 is approximately uniform for constant values of  $r$ , i.e., along arc 1012. When the incident x-ray beam 1004 is at a Bragg angle for a given plane of the polycrystalline material 1010, there is a peak in the intensity of the diffracted x-rays 1006 along arc 1012.

Referring to FIG. 2, a Portable X-Ray Diffractometer (PXRD) assembly 10 includes two main components, a scanning head 12 and a control housing assembly 14. In one preferred embodiment, a battery 16 powers the PXRD assembly, which is typically an automotive or marine 12-volt battery. In another preferred embodiment, the battery is located within the control housing assembly 14, and in other embodiments, components are arranged in various configurations.

In operation, an operator 2 holds the scanning head 12 against an object 18. The scanning head 12 is made from an x-ray shielding material such as aluminum and is of sufficient thickness to effectively shield the operator 2 from x-rays generated from within the scanning head 12. When the scanning head 12 is in operation and positioned against the object 18, x-rays are used to scan the internal structure of the object 18 by irradiating a target area of the object with an x-ray beam and measuring the diffracted x-ray intensity.

The object 18 is generally a component of a larger system or apparatus. In a non-limiting example, the component can be a landing strut of an aircraft, or pipes or tubes in an electrical power plant or oil refinery. Typically, the PXRD assembly 10 irradiates the object 18 while the object 18 is integrated into the larger system or apparatus. Frequently, the examination of the internal structure of the object 18 is done during routine maintenance of the larger system or apparatus. In a non-limiting example, electrical power plants are frequently shut down for routine maintenance of tubes located in a boiler, the tubes carry superheated steam and are examined in situ by the PXRD assembly 10. In other situations, the PXRD assembly 10 is used to examine components of systems that are in operation. In another non-limiting example, tubes such as those found in an oil refinery or a power plant that are accessible during the operation thereof are examined in situ by the PXRD assembly 10. In yet another non-limiting example, components of systems that are idle, but not disassembled, nor in maintenance mode, such as landing struts of a parked aircraft are examined in situ by the PXRD assembly 10.

The scanning head 12 preferably includes a base 20 and a cover 22, which is pivotally coupled to the base 20 by hinges (not shown), thereby providing the operator 2 access to the components included therein. In one embodiment, the scanning head 12 also includes an LED 24, which is lit when the scanning head 12 is in scanning operation.

The exterior of the scanning head 12 preferably includes cable connectors 26, which provide coupling between internal components of the scanning head 12 and cables 28A through 28D. The internal components of the scanning head 12 are described hereinbelow.

The control housing assembly 14 preferably includes a carrying case 30 that has foldable legs 32 attached thereto. The exterior of the carrying case 30 includes a plurality

of cable connectors 56, which provide coupling for the cables 28A through 28D. Inside of the carrying case 30 are components of the PXR assembly 10, which include an x-ray source controller 34, an x-ray detector controller 36, a data processor 38, a laptop computer 40, and a power inverter 42.

5           The x-ray source controller 34 includes a power switch 34 and voltage and current control knobs 46. The x-ray source controller 44 is electrically coupled to the battery 16 via a power cord (not shown) that extends from the x-ray source controller 34 to a receptacle (not shown), which receives a power cord 52 that extends from the receptacle to the battery 16. The power-cord from the receptacle bifurcates such that the x-ray  
10       source controller 34 and the power inverter 42 are both in electrical communication with the battery 16. Extending from the x-ray source controller 34 to the backside of cable connectors 56 is a cable 54, which is typically a 12-wire bundle terminated with AMP CPC 17-16 type connector. The cable 54 is in electrical communication with an x-ray source (not shown) located in the scanning head 12 via cable 28A. The x-ray source  
15       controller 34 sends electrical power and control information to the x-ray source via cables 54 and 28A. The x-ray source controller 34 is configured, among other things, to initiate the operation of the x-ray source. Typically, initiation involves the x-ray source controller 34 regulating the electrical power delivered to the x-ray source such that the x-ray source is warmed up and brought to operation power in increments. In the preferred  
20       embodiment, the x-ray source controller 34 includes a plurality of LEDs that indicate whether the x-ray source controller 34 is in operation mode or warm-up mode.

          The x-ray detector controller 36 is coupled to the power inverter 42 via power-cord 63 and to the cable connectors 56 via a cable 58, which is typically a Sony CCXC-12P02 camera cable. The x-ray detector controller 36 includes a control knob 60,  
25       which controls the gain of the x-ray detector (not shown), that is included in the scanning head 12. Power and control information is provided to the x-ray detector (not shown) via cable 58, which is coupled to cable 28B via cable connectors 56.

          The data processor 38 is coupled to the electrical connectors 56 via cable 62, which is typically an RG6/U cable and to power inverter 42 via power-cord 64. The data  
30       processor 38 receives data from the x-ray detector (not shown) that is located in the

scanning head 12, via cable 62, which is in communication with cable 28C through cable connectors 56. The data processor 38 is also coupled to the laptop computer 40 via a cable (not shown), which is typically a small computer system interface (SCSI) cable. Both the image processor 38 and the laptop computer 40 have SCSI ports for communicating.

In one preferred embodiment, the data processor 38 is adapted to receive data from the x-ray detector in the scanning head 12 and generate an image that represents the intensity of the reflected x-rays. The data processor 38 also includes an output port (not shown) for connecting a video monitor (not shown) to the data processor 38. Typically, the video monitor is a Sony monitor, such as model HPVM1354Q High Resolution RGB monitor, or the like and the video output port is a VGA port. Typically, the video monitor is used by the operator 2 for viewing the intensity of the reflected x-rays, which will be discussed in detail hereinbelow.

In one preferred embodiment, the computer 40 receives image parameters and/or data from the data processor 38 and further analyzes it using logic such as Peakfit to determine among other things the full width at half maximum of the image. The computer 40 may also include a CD burner (not shown) or DVD burner (not shown), which is used to store the data from the data processor 38 and/or other information. By storing the information on a CD or DVD or in some other medium, a snap-shot in time of the current characteristics of the object 18 is preserved. In the future, different snap-shots in time of the characteristics of the object 18 can be compared as part of the analysis or change of the internal structure of object 18.

The computer 40 is coupled to a serial cable 68 that extends from the computer 40 to the cable connectors 56. The computer 40 is in communication with a photo-spectrum analyzer located in the scanning head 12 via serial cable 68, which is in communication with cable 28D via cable connectors 56. The computer 40 receives spectral data from the photo-spectrum analyzer, which is then used to identify the composition of the object 18. Frequently, similar components of a system are replaced during the lifetime of the system, and as new alloys become available, the components are replaced with components having different alloys. The spectral characteristics of the object enables the operator 2 to



identify the alloy of the object 18. In one embodiment, the computer 40 includes a database of spectral characteristics for materials so that the computer can identify the composition of the object 18.

5 In one preferred embodiment, the computer typically includes an input/output interface (not shown) such as, but not limited to, a modem or Ethernet card for communicating with a central office computer 74 via communication link 72 at a central office 70. The communication link 72 can be the Internet, a modem connection over a telephone system, a wireless connection, or other communication path known to those skilled in the art. Information such as, but not limited to, spectral data, image data, raw  
10 X-ray count data, line shape data/parameters, can be transmitted to the central computer 74 via communication link 72. Data from the photo-spectrum analyzer may also be stored on a CD burned by the CD burner and the CD can be provided to the central office computer 74.

Typically, the computer 40 is configured to process data from the scanning  
15 head 12 in addition to sending information to the central office computer 74. The computer 40 includes processing logic that enables it to average x-ray intensities for pixels that have the same radial distance from central axis 1005, and data fitting logic to fit data to various mathematical models, such as, but not limited to "Peakfit" by Jandel Scientific Software.

20 At the central office 70, the central office computer 74 receives information from the portable computer 40 and processes the information to determine among other things, the remaining lifetime of the object 18. The central office computer 74 includes database 76 and correlation logic 78. When the central office computer 74 receives information from the laptop computer 40 the central office computer 74 implements the  
25 correlation logic 78 to determine the remaining lifetime of the object 18. The database 76, includes among other things, results from crystalline analysis of test objects having crystalline and polycrystalline composition, results of structural integrity analysis of test objects, which can include both destructive and non-destructive tests, and photo-spectrum results of test objects. The correlation logic 78 analyzes the information from  
30 the laptop computer 40 and correlates the crystalline characteristics of the object 18 with

the information in database 76 to determine the remaining lifetime of the object 18. Typically, the information from the laptop computer 40 includes a mathematical representation of the x-ray diffraction pattern of the object 18. The information from the laptop computer 40 can also include both composition information such as the photo-spectrum analysis of the object 18 and crystalline information of the object 18. The information from the laptop computer 40 may further include raw data from the PXRD assembly 10, or partially analyzed data, which could have been partially analyzed by the image processor 38 or by the laptop computer 40.

Refer to FIG. 3, the scanning head 12 includes an x-ray source 80 mounted to a mounting plate 82, which is mounted to the base 20 of the scanning head 12. In an alternative embodiment, the base 20 includes a bottom wall that forms the mounting plate 82.

The x-ray source 80 receives power and operating parameters from the x-ray source controller 36 via cable 84, which extends from the x-ray source 80 to cable connectors 26, where cable 84 is in communication with cable 28A. The operating parameters from the x-ray source controller 34 include current and voltage settings for regulating the intensity and energy of the x-rays generated by the x-ray source 80. The x-ray source 80 also receives signals that put the x-ray source 80 in warm-up mode and in operating mode. The LED 24 receives electrical power from the x-ray source 80 via a pair of electrical wires 86.

In operation mode, the x-ray source 80 emits x-rays that are directed at the object 18 through a window 90 that is formed in the base 20. Disposed between the window 90 and the x-ray source 80 are a pair of collimating apertures 92 that collimate the x-ray beam 94. The x-ray beam 94 is incident upon object 18 where it is then reflected into the scanning head 120.

An x-ray detector 96, receives the reflected x-rays 98. The x-ray detector 96 is mounted to the mounting plate 82 and has cables 106 and 108 extending therefrom to the cable connectors 26. Through cable 106, which is typically a Sony CCXC-12P02 camera cable, and cable 28B, which is in communication with cable 106 through cable connectors 26, the x-ray detector 96 receives operating parameters from the x-ray detector

controller 36. The operating parameters include information for, among other things, setting the gain of the x-ray detector 96.

Cable 108 is in communication with cable 28C via cable connectors 26, and is used for sending x-ray data from the x-ray detector 96 to the image processor 38. In one preferred embodiment, the x-ray detector 96 is a charge-coupled device (CCD) such as a Hamamatsu Photonics CCD Camera, model number C4541 that includes a grid of pixels for detecting x-rays. When one of the pixels is struck by an x-ray, an electrical signal is produced and is associated with the pixel. The x-ray detector 96 records which pixels are struck by an x-ray over a period of time, and then sends that information to the image processor 38. In an alternative embodiment, each time a pixel is struck by an x-ray, the x-ray detector 96 sends a signal that is associated with the pixel, to the data processor 38.

In one preferred embodiment, the x-ray source 80, the collimating apertures 92, and the x-ray detector 94 are removably coupled to the mounting plate 82 in a pre-defined alignment. For example, in the configuration illustrated in FIG. 2, the x-ray source 80 and collimating apertures 92 are aligned such that the angle between the x-ray beam 94 and a specific crystallographic plane of atoms in the object 18 is alpha. Similarly, the x-ray source detector 96 is aligned such that the angle between a portion of the detected reflected x-ray beam 98 and the specific crystallographic plane is also alpha. In one embodiment, the x-ray source 80 and the collimating apertures 92 and the x-ray detector 96 are each removably mounted to the mounting plate 82 by pins (not shown) extending into bores (not shown) formed in the mounting plate 82. The mounting plate 82 includes multiple bores for configuring the x-ray source 80, the collimating apertures 92, and the x-ray detector 96 in other predefined alignments. For example, in a second configuration, the pins of the x-ray source 80 and the pins of the collimating aperture are received by bores 100 and 102, respectively. Similarly, bores 104 receive the pins of the x-ray detector 96. In the second configuration, the x-ray source 80 and the collimating apertures 92 are aligned such that the angle between the incident x-rays and the reflecting plane of atoms is beta, as is the angle between a portion of the detected diffracted x-rays 98 and the reflecting plane of atoms.

The predetermined alignment of the x-ray source 80, the collimating apertures 92, and the x-ray detector 96 are determined with respect to the crystallographic characteristics of the object being scanned. In table 1, exemplary materials and the Bragg angle for specific crystallographic planes of the materials are listed for Cu K $\alpha$  x-rays. In one preferred embodiment, the mounting plate 82 includes multiple alignment bores 100, 102, and 104 for aligning the x-ray source 80, the collimating apertures 92, and the x-ray detector 96 for each of the Bragg angles listed and for other Bragg angles for other materials and crystallographic planes not listed. The Bragg angle is a function of the wavelength of the x-rays and changes for x-rays of different wavelengths.

**Table 1**

Material	Plane	Angle
Fe	110	22.3 degrees
Al	200	22.4 degrees
Si	220	23.7 degrees
Si	111 (second order, n=2)	29.5 degrees
Fe	200	32.5 degrees
Al	220	32.6 degrees
Si	400	34.5 degrees

Due to the physical characteristics of the object 18, the incident x-ray beam 94 is not reflected as a collimated beam, rather, the beam is diffracted. The x-ray detector 96 is aligned such that a peak in the intensity of the diffracted x-rays 98 is observed at the approximate vertical center of the target window (not shown) of the x-ray detector 96. The scanning head 12 also includes a photo-spectrum analyzer 110, which is mounted to mounting platform 82.

When the incident x-ray beam 94 irradiates the object 18, the object 18 fluoresces, and the photo-spectrum analyzer 110 measures the intensity of the fluoresced light across a frequency range. The spectral characteristics of the object 18 are then sent to the laptop computer 40 via cable 112, which is in communication with cable 28d via cable connectors 26.

Refer now to FIG. 4, in an alternative embodiment, the scanning head includes a pivotable shutter assembly 114 and a window frame 91. The window frame 91 frames window 90 and is mounted on mounting plate 82.

The pivotable shutter assembly 114 includes a hinge mount 116 that is rigidly affixed to the window frame 91 by a pair of mounting pins 120. The mounting pins 120 extend through the hinge mount 116 into bores (not shown) that are formed partially through the window frame 91. In alternative embodiments, the hinge mount 116 is coupled to the base 20 or to cover 22 by fastening means such as screws, bolts, rivets and other fasteners known to those skilled in the art, or by affixing means such as, but not limited to, glue or welding.

The hinge mount 116 includes opposed ends 124 and 126 that extend generally downward. Opposed ends 124 and 126 each define a bore 128 for receiving a pin 118. The bores 128 are of greater diameter than pins 118 so that the pins 118 are rotatable when in operation position. The bore 128 of end 126 extends through the end 126 so that the pin 118A extends therethrough.

The pivotal shutter assembly 114 includes a plate mount 130 and a shutter 132 rigidly coupled to the plate mount 130 by a plurality of pins 134, or other fasteners known to those skilled in the art. The plate mount 130 includes bores 136 for receiving pins 118, which are firmly pressed therein such that they are not independently rotatable.

The plate mount 130 extends between the opposed ends 124 and 126 such that the shutter 132 covers the window 90 when the shutter 132 is rotated downward. Disposed between the plate mount 130 and the end 126 of hinge mount 116 is a coil spring 138, which is firmly attached to pin 118A and to the hinge mount 116. The spring 138 is configured to apply a biasing force on pin 118A so that the shutter 132 is biased towards the closed position.

A cam 140 is rigidly pressed onto the pin 118A and is coupled to a solenoid 142 via a wire 144. The solenoid 142 is in electrical communication with a pair of pressure switches 88 via electrical wire 87, which extends from the x-ray source 80. In the preferred embodiment, the pressure switches 88 are connected in series so that both of the pressure switches 88 must be closed to actuate the solenoid 142. The pressure switches 88 are disposed on the exterior of the scanning head 12 proximal to the window 90 so that they are actuated when the window 90 is pressed against the object 18. In an alternative embodiment, the pair of pressure switches 88 are replaced by a single pressure switch.

In operation mode when the pressure switches 88 are closed, the solenoid 142 is actuated, thereby upwardly retracting wire 144. The upward motion of wire 144 causes the shutter 132 to rotate upward about the axis defined by pins 118, thereby uncovering window 90.

In this embodiment, the shutter 132 is made from an x-ray shielding material such as aluminum and is of sufficient thickness to effectively shield the operator 2 from x-rays generated by the x-ray source 80 by covering the window 90. If the scanning head 12 is moved such that the window 90 is no longer proximal to the object 18, then the pressure switches 88 would no longer abut the object 18 and they would not be actuated. When the pressure switches are not actuated, the solenoid 142 is not actuated and the shutter 132 is biased to cover the window 90 by the spring 138.

In one embodiment, the pressure switches 88 control power to the x-ray source 80 so that the x-ray source 80 cannot generate x-ray unless the pressure switches 88 are actuated.

Referring to FIG. 5, the x-ray source controller 34 includes a power supply 502 that converts A/C electrical power into D/C electrical power. When A/C power is not available, the external battery 16 is connected to the nodes 504 to provide electrical power to the x-ray source controller 34. The x-ray source controller 34 includes a time delay switch 506, the power switch 44, pins 510(a) through 510(i), an LED 512 and an LED 514. Each LED 512 and 514 is in series with a resistor 518, which is typically in the 1000 Ohm range. When the power switch 44 is initially closed, the time delay switch

is open and power is provided to LED 512 and to pin 510(b). LED 512 is used for indicating to the operator 2 that the x-ray source 80 is in warm-up mode. After a predetermined amount of time, typically around 60 seconds, the time delay switch 506 closes and power is provided to LED 514 and to pin 510(a). The LED 514 indicates to the operator 2 that the x-ray source 80 is now in operation mode. The pins 510(a) through 510(i) are coupled to the x-ray source 80 via cable 28(a). Pin 510(a) is the operating power pin, which is in electrical communication with the pressure switches 88 and provides the operating power to the x-ray source 80. Pin 510(c) is a common connector that provides a reference point for measuring potential differences and is at 12V common.

Pins 510(d) through 510(h) are used for setting operating parameters in the x-ray source 80 using potentiometers 516(a) and 516(b), which control the current and voltage in the x-ray tube respectively. The potentiometers 516 are adjusted by the operator 2 using the control knobs 46. Adjustment of the potentiometer 516(a) changes the voltage between pins 510(d) and 510(e), thereby changing the current within the x-ray tube. Similarly, the adjustment of potentiometer 516(b) changes the voltage between pins 510(h) and 510(g) thereby changing the voltage in the x-ray tube. Pin 510(i) is the chassis ground pin for the x-ray source 80 and the x-ray source controller 34.

## **Experimental Results**

In this section experimental results for an exemplary metal (brass) are given using an exemplary battery-powered x-ray diffractometer. For the experiment described herein the x-ray source was a Kevex, model no. PXS5, Cu anode x-ray source, the x-ray detector was a Hamamatsu Photonics Detector, model no. C4541 intensified CCD camera for x-ray imaging, and the data processor was a Hamamatsu Photonics, model no. C5510 Argus-20 image processing system.

The experimental results are shown in FIGs. 6A, 6B and FIG. 7. In this experiment, the brass specimen that was irradiated by the Kevex x-ray source for 8 hours with the x-ray source set at its maximum output. The dark vertical band 602 (shown in

FIG. 6A and 6B) which is in the approximate vertical center of the image is the detected peak in the diffracted x-ray intensity.

The x-ray detector detected x-rays using a grid of pixels. When an x-ray strikes a pixel it causes an electrical signal to be generated, which is associated with the struck pixel. Thirty times per second the x-ray detector sends the image processor data that identified which pixels had been struck in the preceding 1/30 second.

The image processor generates the image shown in FIG. 6A and 6B by counting the number of detected x-rays for each of the pixels and associating a gray scale value for each pixel. The pixels that have the highest number of detected x-ray strikes are represented by the darkest areas in FIG. 6A and 6B.

The image shown in FIG. 6A includes background noise, and FIG. 6B is the detected x-ray intensity with the background noise subtracted out. The background noise was caused by x-rays that were reflected into the x-ray detector from sources other than the target area of the object, i.e., the brass specimen. The background noise is related to the configuration and components used in the experiment. Thus, in one preferred embodiment, in a controlled environment, the background noise is measured in the scanning head so that the background noise can be subtracted out. The background noise for a specific alignment and configuration is determined by aligning the x-ray source 80, the x-ray detector 96, the collimating apertures 92, and the photo-spectrum analyzer 110 in the specific configuration and with the shutter window 90 uncovered and having the x-ray source 80 emit an x-ray beam through the window 90. For background noise measurements, there is no target to reflect or scatter the x-rays that pass through the window 90 back into the scanning head 12. Because there is no target, there are no fluorescent x-rays. Therefore, the x-rays that the x-ray detector 96 counts are those x-rays that are reflected off of components within the scanning head 12. Generally, the background noise is reduced by choosing the collimating apertures 92 such that the x-ray beam that exits the collimating apertures is narrow and focused upon the target area of the object 18.

Although the dark band 602 in FIGs. 6A and 6B appears approximately linear it corresponds to the arc 1012 in FIG. 1C. The x-ray intensity is processed such that the



x-ray count for pixels that are the same radial distance ( $r$ ) from the central axis 1005 are averaged together.

5 In FIG. 7 the average pixel intensity is graphed versus the radial distance from the central axis 1005. Each dot in FIG. 7 represents the average number of x-ray strikes for pixels that have the same radial distance. The solid line 702 is a parameterized fit of the data points using a Pearson VII function. In one embodiment, the data is fit using a computer program known to those skilled in the art such as Peakfit. The output of the parameterized fit includes values such as the full width at half maximum, which is used to establish a measure of the crystalline structure of the object. The width of the peak is  
10 directly related to the crystalline characteristics of the object. The more defects and imperfections in the crystal, the greater the width of the peak.

Refer now to FIG. 8, steps 800 are implemented by computer 40 to average the x-ray intensities for pixels having the same radial distance from the central axis 1005. In step 802 the computer determines three pixels that are equidistant the central axis 1005.  
15 The three pixels are chosen such that they are approximately in the bottom 1/3, the middle, and the top 1/3 of the dark vertical band 602. In the preferred embodiment, the x-ray detector 80 is aligned such that the dark vertical band 602 is approximately vertical with respect to the horizontal pixels of the x-ray detector 80, and the computer 40 calculates the approximate center of the dark vertical band 602 for horizontal arrays that are in the bottom 1/3, the middle, and the top 1/3 of the pixel grid. One method for  
20 finding the approximate center of the dark vertical band 602 for a horizontal pixel array is to associate each pixel of the horizontal array with an average intensity; where the average intensity is calculated from the intensity of that pixel and a predetermined number of horizontal neighbors. The average intensity will typically be greatest in the center of the dark band 602. Thus, for each of the three horizontal pixel arrays, the  
25 computer chooses the pixel that is associated with the greatest averaged intensity and determines the radial distance from the central axis 1005 to that chosen pixel.

In step 804, the computer 40 relates the radial distance from the central axis 1005 to the three chosen pixels in terms of pixel widths and calculates the radial distance for all  
30 of the other pixels.

In step 806, the computer 40 averages the x-ray intensities of pixels that have the same radial distance from the central axis 1005. In one embodiment, the radial distance from the central axis 1005 is then related to scattering angle, the angle between the central axis 1005 and the diffracted x-ray. In that case, the line width shown in FIG. 7  
5 would be intensity versus scattering angle.

It should be emphasized that the above-described embodiments of the present invention, particularly, any “preferred” embodiments, are merely possible examples of implementations, merely set forth for a clear understanding of the principles of the invention. Many variations and modifications may be made to the above-described  
10 embodiment(s) of the invention without departing substantially from the spirit and principles of the invention. All such modifications and variations are intended to be included herein within the scope of this disclosure and the present invention and protected by the following claims.